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Estimating permeability using the parameter estimation method in a high-permeability area of the Kurobe River alluvial fan, Japan

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Abstract

The parameter estimation (PEST) method was used to estimate the spatial distribution of permeability coefficients in a high-permeability area of the Kurobe River alluvial fan in Toyama Prefecture, Japan. We considered spatial resolution, estimated period, soil structure, recharge source, and boundary conditions in the model. Numerical experiments produced estimated permeability coefficients that were consistent with the observed data and those of previous studies under all conditions. However, the estimated groundwater levels were lower than those of previous studies. Spatial resolution and the number of foundation layers did not have a large effect on estimates of the vertical permeability coefficient (k_z). However, recharge source and boundary conditions were important for estimating permeability coefficients. Finally, the estimates of specific storage (S_s) and specific yield (S_y) were similar to the observed data under all conditions.

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1. Introduction

Groundwater has been an invaluable source of freshwater globally since ancient times. Before the advent of modern drilling technology, groundwater was primarily exploited through natural springs and flowing wells. However, since the development of drilling technology, much larger amounts of

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groundwater are now pumped out of aquifers for domestic as well as agricultural and industrial uses. In Japan, the Southern part of the Kanto Plain has shown settling or subsidence since the first half of 1890s due to excessive groundwater pumping; the Osaka Plain has shown similar effects since the 1930s. In fact, widespread groundwater issues have been occurring throughout Japan since 1955. Thereafter, land subsidence has been mitigated through strict pumping regulations and shifts to other freshwater sources [1]. However, groundwater still comprises approximately 20% of Japan's water supply, and remains the primary source for domestic use in several regions. Moreover, after the Great East Japan Earthquake in 2011, the role of groundwater sources has been reconsidering in an emergency the importance of groundwater as an emergency freshwater supply has gained new appreciation.

The cumulative effects of excessive groundwater exploitation are considerable. A recent study [2] suggested that groundwater extraction is a significant cause of the increasing sea water levels worldwide. The study showed that unsustainable groundwater use, artificial reservoir water impoundment, climate-driven changes in terrestrial water storage, and the loss of water from closed basins have contributed ~42% of the total observed sea-level rise. Studies into the direct effect of climate change on groundwater sources have considered several potential mechanisms, including the effect of hydrological change on recharge, saline intrusion into aquifers due to sea level rise, and the effect of changes in the temporal and spatial distribution of precipitation on groundwater recharge. However, these studies reflect merely the effects of air temperature and precipitation on groundwater; in fact, very few studies have examined the direct relationship between climate change and the groundwater environment [3], [4].

The Kurobe River alluvial fan (KRAF), located in the Hokuriku region, is the most highly utilized alluvial fan in Japan; this aquifer supported many flowing or artesian wells in ancient times. However, previous authors have reported decreasing groundwater levels from the KRAF over the past 20 years [5], and have been monitoring over 20 flowing wells [6]. Alluvial fans are characterized by a complex heterogeneous soil structure that forms as a result of debris accumulating over repeated inundations. Thus, hydrofacies with differing permeabilities are deposited gradually over time and boring tests typically show frequent changes in permeability coefficients as each of these hydrofacies is breached. This complexity has consequences in terms of our ability to characterize and understand such an environment. This is because although modeling is often used to study heterogeneous aquifers (as a means to compensate for our lack of information regarding the deep underground), the high complexity and heterogeneity of alluvial fans means that these bodies are typically simulated as a simplified single, homogeneous layer. The objective of this study was to better clarify the groundwater hydraulic environment and improve the accuracy of groundwater modeling by using an inverse estimation method to simulate hydraulic parameters in an alluvial fan.

2. The Kurobe River alluvial fan

2.1. Geomorphological features

Fig. 1 shows a map of the Kurobe River basin located in Toyama Prefecture, central Japan. The 85-km-long river originates at an altitude of 2,924 m in the northern Alps of Japan and flows into the Japan Sea. The catchment of the Kurobe River basin covers 682 km², and the KRAF, on which this study was based, covers approximately 120 km². The difference in elevation from Aimoto at the top of the alluvial fan to sea level is 130 m, and the slope of the alluvial fan is 1/100. The alluvial fan consists of several conglomerate layers. Land use on the KRAF is mostly paddy fields. There are also many flowing wells in the fan, which have long supplied groundwater for domestic and agricultural purposes.

2.2. Hydrological characteristics

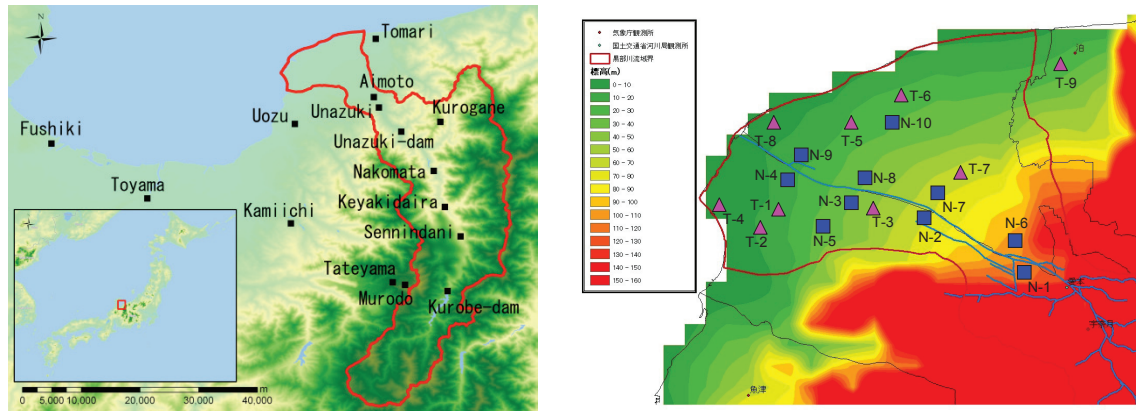


Fig. 1. (Left) Map of the Kurobe River basin (outlined in red) and an inset map of Japan showing the location of Toyama Prefecture (red square). (Right) Map of the Kurobe River alluvial fan (KRAF) and the locations of groundwater observation wells.

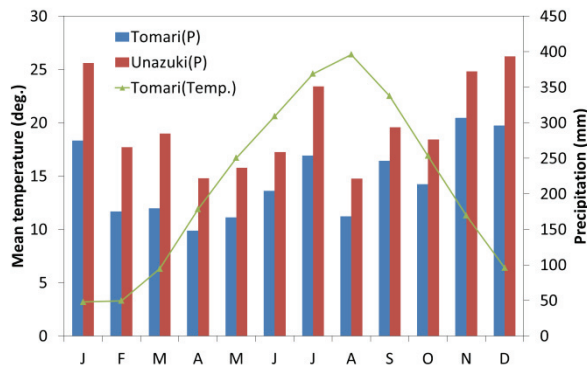


Fig. 2. Monthly mean temperatures and precipitation levels at the Tomari and Unazuki meteorological stations, averaged over 1981 to 2010.

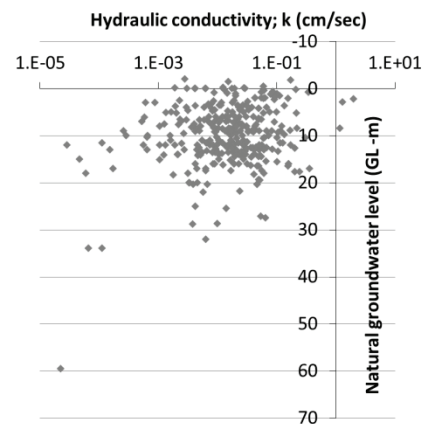


Fig. 3. Relationship between hydraulic conductivities and natural groundwater levels in the KRAF.

Fig. 2 shows the monthly mean temperature and precipitation data at Tomari and Unazuki (averaged over 1981 to 2010). The basin has four marked seasons: spring (March to May; MAM), summer (June to August; JJA), autumn (September to November; SON), and winter (December to February; DJF). The climate of the Kurobe River basin is cold with heavy snowfall in winter and hot and humid in summer, with heavy rainfall. Annual precipitation increases in an upstream direction, rising from 2000 mm at Kurobe on the plain, to 3000 mm at Unazuki in the middle reaches, and finally to 4000 mm at Sennindani in the mountains. Accordingly, flood risk is high in June and July during the Baiu rain front season. Heavy snowfall from December to March contributes to plentiful water resources. Annual mean air temperatures are 14°C at Kurobe dam, 12°C at Unazuki, 9°C at Sennindani, and 14.2°C at Tomari.

Regarding groundwater usage, 474 wells in Kurobe city and 921 wells in Nyuzen town were drawing on the KRAF as of 31 March 2013. Based on data from 346 of these wells, for which pumping water

levels, natural groundwater levels, and pumping data were available, hydraulic conductivities for the surrounding aquifer were estimated via the following four steps, as described by Logan [7]:

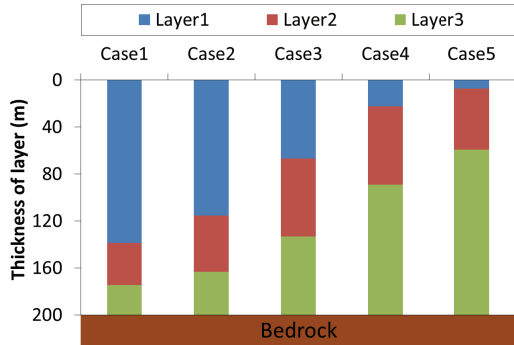


Fig. 4. Layer thickness conditions used in the numerical simulations.

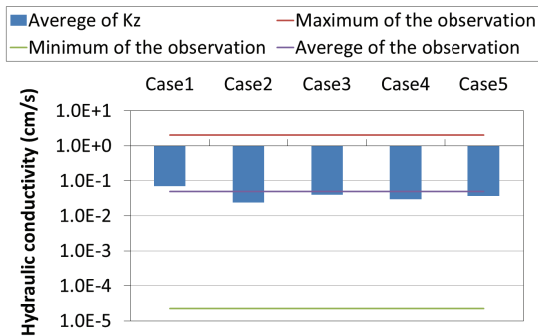


Fig. 6. Inverse analysis results for estimated vs. observed mean hydraulic conductivities for Case 1 through Case 5.

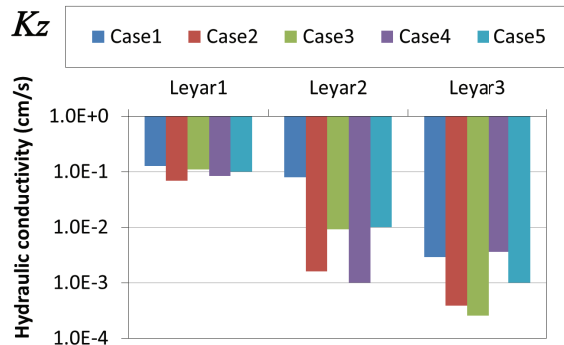


Fig. 5. Inverse analysis results for hydraulic conductivities (K_z) estimated for Case 1 through Case 5.

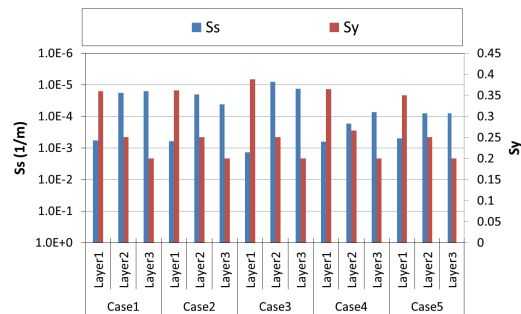


Fig. 7. Inverse analysis results for specific storage (S_s) and specific yield (S_y) for Case 1 through Case 5.

$$\Delta s = GWp - GWn \quad (1) \quad Q_{sc} = \frac{Qp}{\Delta s} \quad (2)$$

$$T = 1.22 \times Q_{sc} \quad (3) \quad k = \frac{T}{L} \quad (4)$$

where Δs is depression head, GWp is pumping water level, GWn is natural water level, Q_{sc} is specific capacity, Qp is pumpage, T is transmissivity, k is hydraulic conductivity, and L is strainer length. Fig. 3 shows the relationship between hydraulic conductivity and natural groundwater levels in the KRAF. The maximum hydraulic conductivity was 2.02 cm/s, the minimum was 2.24×10^{-5} cm/s, and the average was 4.90×10^{-2} cm/s. The most frequently observed hydraulic conductivity values (54.7% of all values) ranged between 10^{-2} and 10^{-1} cm/s. The frequency of sites showing hydraulic conductivities less than 10^{-2} cm/s was 35.8%. Another 9.5% of sites showed values greater than 10^{-1} cm/s, which were deemed high-permeability sites. Many shallow (<30 m) natural groundwater wells were observed. Natural groundwater levels and hydraulic conductivities showed a proportional relationship.

3. Numerical simulation

3.1. MODFLOW

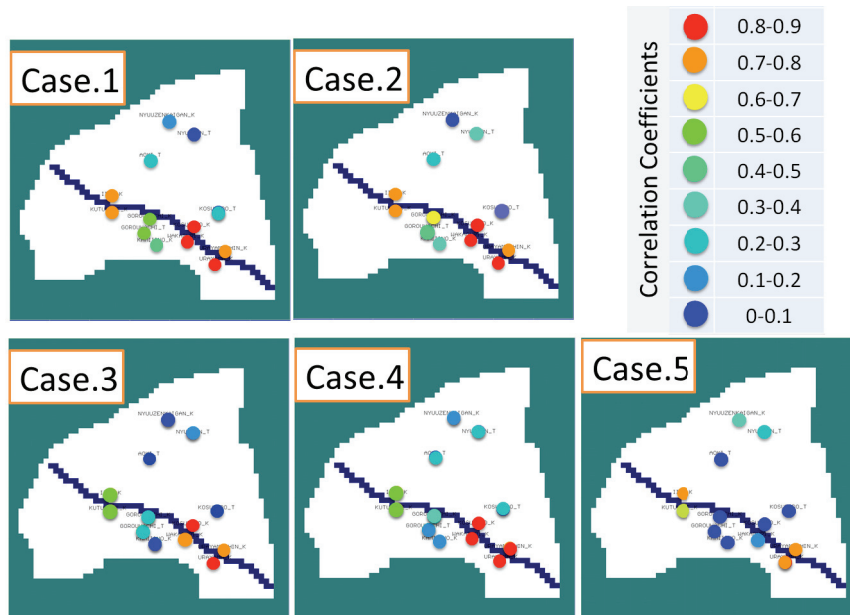


Fig. 8. Simulation results and correlation coefficients for daily observed vs. simulated groundwater levels in Case 1 through Case 5.

Two previous studies examining the KRAF developed steady- and non-steady-state three-dimensional groundwater models [8], [9]. These models were validated based on the simulation results for recharge data. Moreover, using a groundwater equipotential distribution map, groundwater ridges along the Kurobe River were estimated. In a recent study, a detailed, distributed, hydrological model was developed for the Kurobe River basin that included not only the natural system, but also artificial features such as groundwater pumping [10]. This model, which used a 1×1 km mesh, was used to clarify the mechanisms of recharge and spring flow from the Kurobe River. This study used MODFLOW-2005 [11], which was developed by the U.S. Geological Survey (USGS), is freely available to the public, making it the most popular groundwater model worldwide. MODFLOW in combination with climate models have been used to estimate the effect of climate change on recharge and groundwater levels in British Columbia, Canada, and on the groundwater environment in southern Finland. Moreover, MODFLOW has been used within Japan for numerical modeling of the effect of land use change and groundwater pumping rate on groundwater levels in the Tedoru River alluvial fan.

The governing equation was derived using the mass conservation law (Eq. 5) and Darcy's law (Eq. 6), as follows:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = -S_s \frac{\partial h}{\partial t} + R^* \quad (5)$$

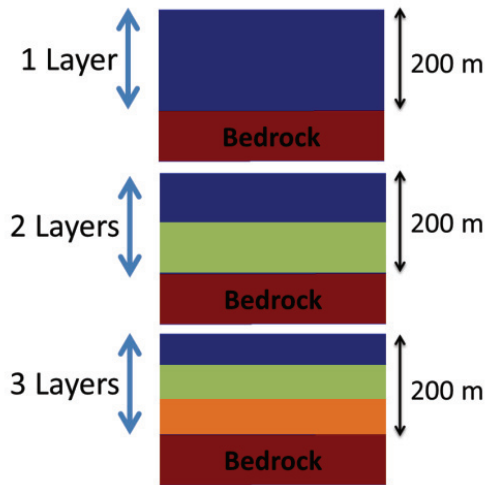


Fig. 9. Numerical experimental model for assessing the effect of number of layer thicknesses.

$$q_x = -K_x \frac{\partial h}{\partial x}, q_y = -K_y \frac{\partial h}{\partial y}, q_z = -K_z \frac{\partial h}{\partial z} \quad (6)$$

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t} + R^* \quad (7)$$

where, K is hydraulic conductivity (L/T), S_s is specific storage (L-1), R^* is intake/ source term (T-1) and h is hydraulic head. MODFLOW uses the finite-difference method for time and space. The model area was set at 16×16 km, which is wider than the actual alluvial fan, using a 250×250 -m digital elevation model (DEM); this was done to deal with the potential effects of boundary conditions. To describe the aquifers in as much detail as possible, 283 boring surveys were carried out throughout the entire alluvial fan and were then input to the model. The typical single layer in the model was reclassified into three layers vertically. One of four types of material (surface soil, mixed sand and gravel, mixed sand, gravel, and clay, or the presence of an aquiclude) was indicated for each of these layers. Recharge data made use of mean daily precipitation data collected from the Uozu and Tomari meteorological stations. Assumptions were also made regarding the inundation of paddy fields found within the KRAF. The period of inundation and submerged depth of these paddy fields were based on recommendations made by the local government and agricultural cooperatives to paddy farmers. Regarding boundary conditions, the bedrock was assumed to be non-permeable. Boundary conditions also included the observed tidal data from Toyama bay and observed water levels for Kurobe River. Given that previous research has shown that recharge from the Kurobe River is a very large contributor to the KRAF, the interaction between the river and the aquifer has been previously modeled in detail. A conductance value of 158,215 m²/day/mesh was used for this study, based on historical discharge data.

Table 1. Matrix of initial conditions for hydraulic parameters used in the numerical model.

	No.	changed parameter	number of layers	Hydraulic conductivity (cm/s)			specific storage (1/m)	specific yield (-)
				Kx	Ky	Kz	Ss	Sy
No.1	1-A	K	1	0.01			5E-4	0.3
	1-B	K		0.1			5E-4	0.3
	1-C	K		1			5E-4	0.3
	1-D	Ss		0.1			5E-2	0.3
	1-E	Ss		0.1			5E-5	0.3
	1-F	Sy		0.1			5E-4	0.01
	1-G	Sy		0.1			5E-4	0.5
No.2	2-A	K	2	0.01			5E-4	0.3
	2-B	K		0.1			5E-4	0.3
	2-C	K		1			5E-4	0.3
	2-D	Ss		0.1			5E-2	0.3
	2-E	Ss		0.1			5E-5	0.3
	2-F	Sy		0.1			5E-4	0.01
	2-G	Sy		0.1			5E-4	0.5
No.3	3-A	K	3	0.01			5E-4	0.3
	3-B	K		0.1			5E-4	0.3
	3-C	K		1			5E-4	0.3
	3-D	Ss		0.1			5E-2	0.3
	3-E	Ss		0.1			5E-5	0.3
	3-F	Sy		0.1			5E-4	0.01
	3-G	Sy		0.1			5E-4	0.5

The period of analysis was 1000 days from 1 December 2004 to 27 August 2007, for which groundwater, river, and precipitation data were complete (no missing values).

3.2. PEST

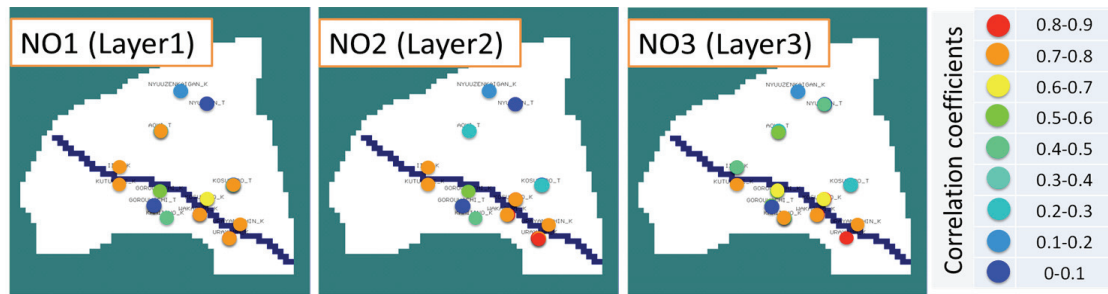


Fig. 10. Simulation results and correlation coefficients for daily observed vs. simulated groundwater levels.

This study used the open-source PEST algorithm to optimize hydrological parameters [12], [13]. This algorithm uses the Gauss–Marquardt–Levenberg method, which is the most robust method for solving nonlinear least-squares problems. This approach combines the Gauss–Newton method and the steepest descent method, which shows excellent results in terms of efficiency and stability. In this paper, a total of 3 groundwater hydraulic parameters were estimated, including the hydraulic conductivities (K_x , K_y , K_z), specific storage (S_s) and specific yield (S_y) for the above-mentioned six layers. In this study, the anisotropy ratios for x , y , and z were 1.

4. Numerical experiment

4.1. Layer thicknesses

Fig. 4 shows the layer thickness conditions for the numerical simulation. The vertical range (200 m until striking bedrock) was divided into three layers.

In Case 3, for example, the vertical range was divided into layers 66.66 m thick. The effect of changes in thickness on hydraulic parameters and the accuracy of simulated groundwater levels was studied. Fig. 5 shows the inverse analysis results of hydraulic conductivities estimated in Case 1 through Case 5.

In general, estimated hydraulic conductivities were large, indicating that the KRAF is highly permeable. Hydraulic conductivities for surface layers were higher, and those of deep layers were lower. To compare estimated and observed data, Fig. 6 shows the inverse analysis results for the mean hydraulic conductivities (K_z) generated for Case 1 through Case 5, as well as the observed K_z values. Overall, estimated K_z values were similar to the average of observed K_z data, suggesting that our model was successful in accurately reflecting the spatial uniformity of hydraulic conductivity K_z . Fig. 7 shows inverse analysis results for specific storage (S_s) and specific yield (S_y) in Case 1 through Case 5. The estimated values for specific storage and specific yield ranged from 10^{-3} to 10^{-5} , which is consistent with the geological structure of an alluvial fan. Fig. 8 shows simulation results for daily observed vs. simulated groundwater levels in Case 1 through Case 5. In all cases, correlation coefficients near the top of the fan were very high, suggesting that groundwater supply from the upper watershed was stable. Correlation coefficients for observation wells at some distance from the river were very small, likely because these areas were affected by recharge from paddy fields.

4.2. Number of layer thicknesses and thicknesses of layer

Fig. 9 shows a numerical experimental model. The vertical range (200 m) was either left as a single layer, or divided into two or three layers (100 or 66.66 m each, respectively).

Table 1 shows a matrix of initial hydraulic parameters used in the numerical models. The number of hydraulic conductivity values (K_x , K_y , K_z), specific storage (S_s) and specific yield (S_y) were used to set initial conditions, as determined in the previous analyses. Fig. 10 shows simulation results for daily observed vs. simulated groundwater levels. As mentioned above, the KRAF is strongly influenced by recharge from the Kurobe River. Accordingly, simulated data for observation wells near to the river showed good accuracy, whereas simulated data for observation wells distant from the river showed very poor correlation coefficients. The number of layer thicknesses included in the groundwater model did not make a significant contribution to repeatability of groundwater level data.

5. Conclusion

The purpose of this study was to better understand the hydraulic environment within the KRAF and to improve the accuracy of groundwater modeling for this body using an inverse estimation method to simulate groundwater hydraulic parameters. As a result of the inverse analysis, estimates for a number of key hydraulic groundwater parameters (permeability, specific storage, and specific yield) were generated. Moreover, groundwater levels simulated using these estimated parameters were highly similar to observed data, especially for observation wells close to the Kurobe River. However, this approach was less successful for wells located at a distance from the river.

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